Trajectory Design Considerations for Small Body Touch-and-Go

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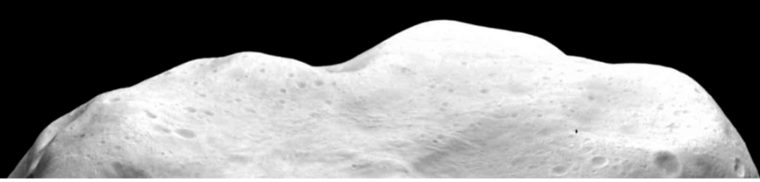
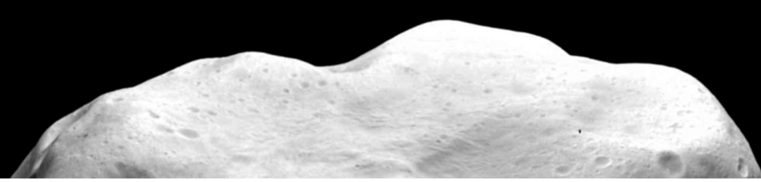


Introduction

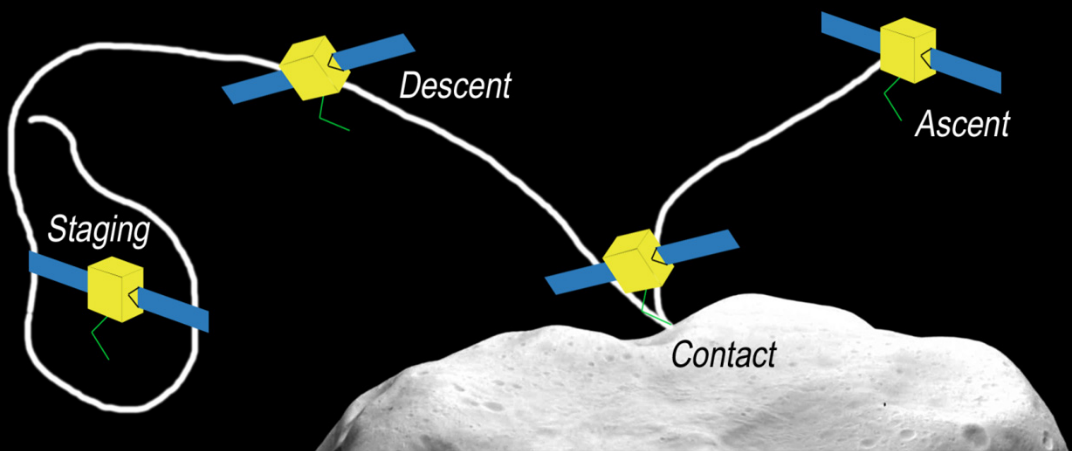
- What is TAG?
  - Descent to the surface
  - Brief contact
  - Ascends to a safe distance
- Why TAG?
  - Sample acquisition, demonstration of landing technology, etc
  - May be preferable to landing
    - Avoid additional hardware
    - Mitigates concerns about topography

- Outline
  - Trajectory Description
  - Design Drivers:
    - Dynamics
    - Environment
    - Spacecraft and Ground System Capabilities
    - Mission Objectives
  - Design Choices
  - Historical Precedents
  - Case Studies



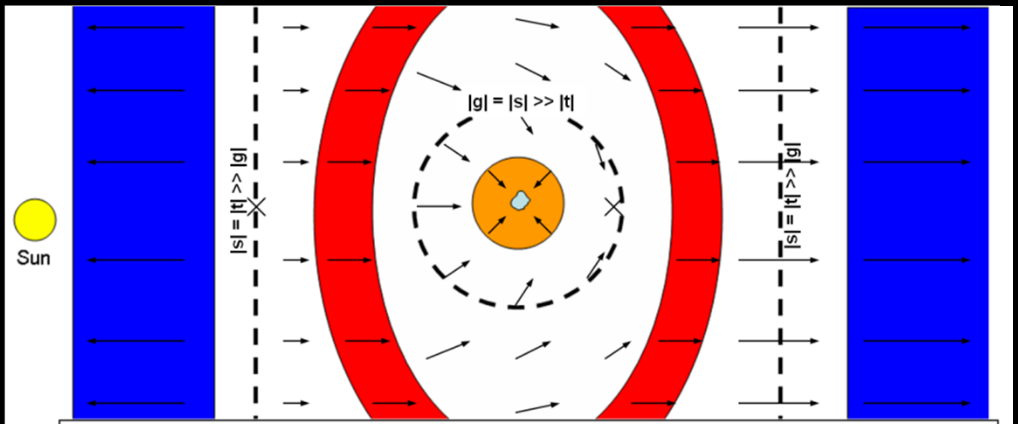
TAG Trajectory Description

- *Staging*
  - Before the commitment is made to go to the surface
  - Flybys, orbits, active stationkeeping
- *Descent*
  - Between staging and contact.
  - Contains most of the maneuvers
- *Contact*
  - On the surface
  - Spacecraft/surface interactions
- *Ascent*
  - From contact to some safe distance
  - Typically initiated with a single burn.

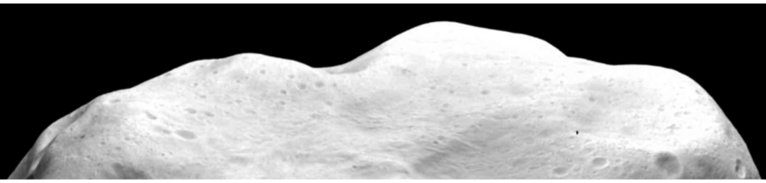


Drivers: Dynamics

- Very complex due to:
  - Non-spherical gravity
  - High SRP relative to gravity
  - Effect of tides
  - Which is dominant varies with position
- Contain atypical effects
  - Coriolis and centrifugal effects
  - Outgassing
  - Secondaries

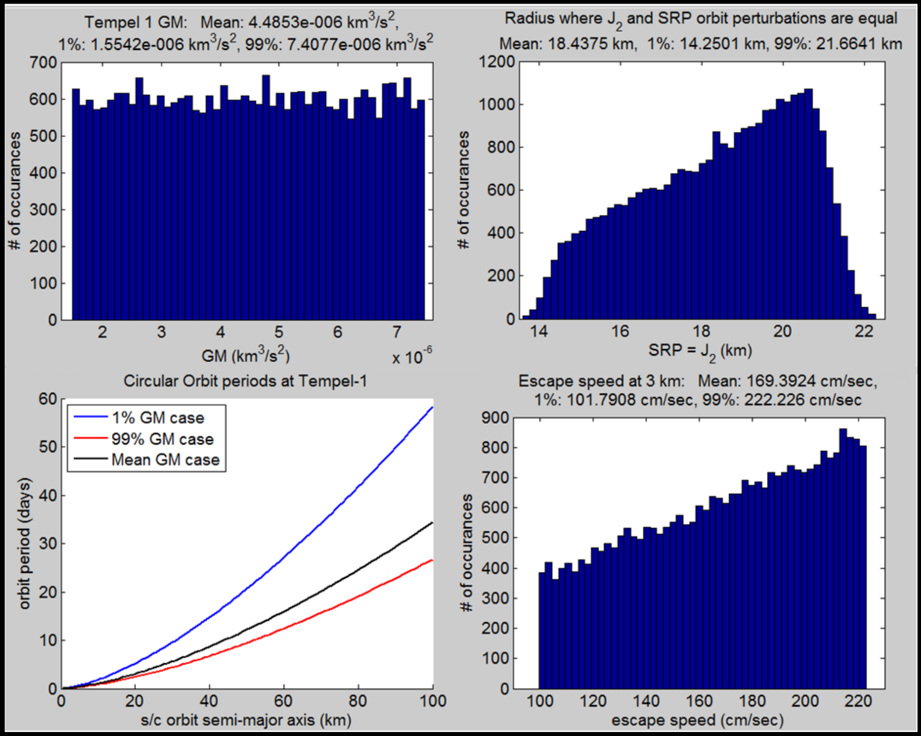


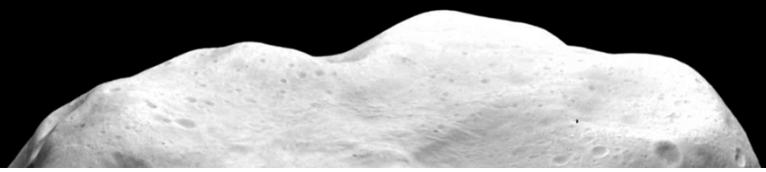
X : Equilibrium, → : Combined acceleration,
Orange: Gravity forces (g) dominate, Red: SRP forces (s) dominate, Blue: Tidal forces (t) dominate



Dynamical Uncertainty

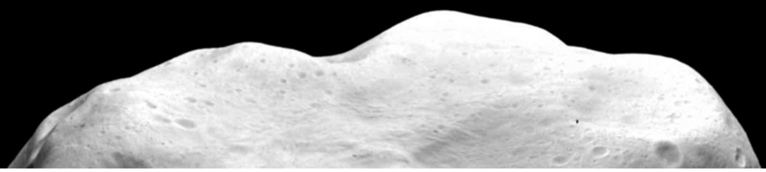
- Dynamics of the small body environment have large uncertainties
  - Limited observations from Earth
  - Available data should be used to bound uncertainty
- Design must be robust to these uncertainties





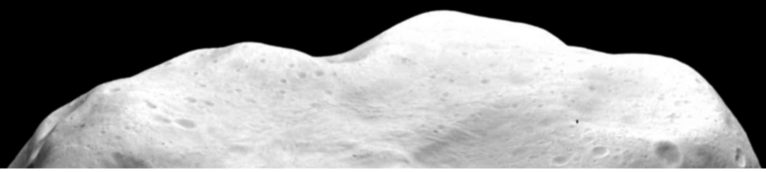
Drivers: Environment

- Orbiting debris and dust
  - TAG event itself can raise significant quantities of dust which may interfere with spacecraft functionality
  - Cometary outgassing can lift dust and rocks (10s of cm) which can cause damage upon impact
- Landing site availability and topography
  - Almost always entirely unknown/unknowable pre-rendezvous
  - Spacecraft may require smooth, obstacle-free sites for successful TAG.
  - Delivery errors should be minimized to increase likelihood that a suitable site can be found.



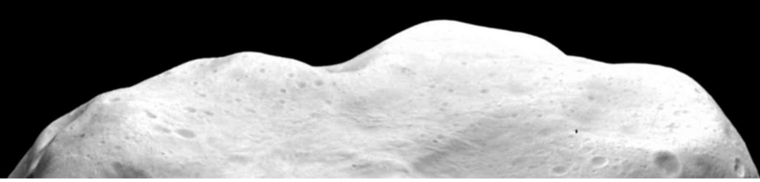
Drivers: Spacecraft and Ground

- Navigation and maneuver capabilities
  - Light time constraints
  - Approach can limit number of manuevers
  - Optical navigation
- Power and Communications
  - Over-constrained geometries
  - Battery depth-of-discharge
- Thrust available
  - Allowable time/distance during contact
  - Moments by surface
- Fault protection
  - Ascent-on-fault
  - Can potentially constrain attitude during descent



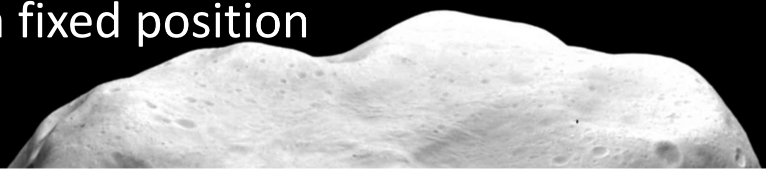
Drivers: Mission Objectives

- Landing site location and contact site accuracy
  - Surface topography typically unknown during mission planning
    - Range of landing sites
    - Ability to adapt
  - Contact state variations may be constrained
    - Samples may be desired from some specific site
    - End-effector works best in a small range
    - Etc.
- Contamination
  - Sample science may require unaltered samples
  - Can constrain maneuvers such as to minimize plume impingement on the surface
  - Can constrain campaign to ability to reach multiple sites
  - Could require special approaches to ascent



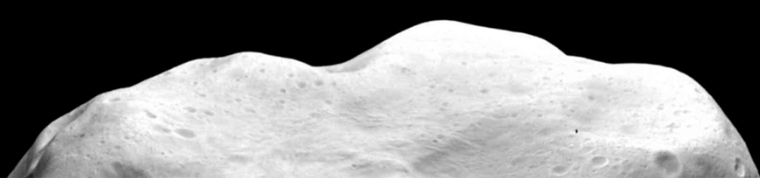
Design Choices (1)

- Staging
  - Gateway between TAG and the rest of the mission
  - Should ensure that the spacecraft remains on a safe trajectory until descent is willfully initiated.
  - Options:
    - Stable orbit
    - Unstable orbits with stationkeeping
    - Ping-pongs
    - Hovering in a fixed position
- Descent
  - Begins and ends motion toward the surface.
  - Includes all the maneuvers to reach the contact state and time
    - Driven by navigation approach
    - Must meet requirements (e.g. contamination)
    - Execution errors
  - Passive abort vs. direct descent



Design Choices (2)

- Contact
  - Lasts a few seconds
  - Complex 6-DOF dynamics due to surface interaction
  - Drivers:
    - Purpose of TAG
    - Contact velocity
    - Spacecraft design
      - Thruster size
      - Allowable stroke
      - Attitude control system
- Ascent
  - "Ascent burn" triggered at contact or shortly thereafter
    - Sized to ensure re-contact doesn't occur
    - Must account for attitude and rate disturbances during contact
  - Single burn or series of smaller burns
    - Contamination
    - Propulsion system type

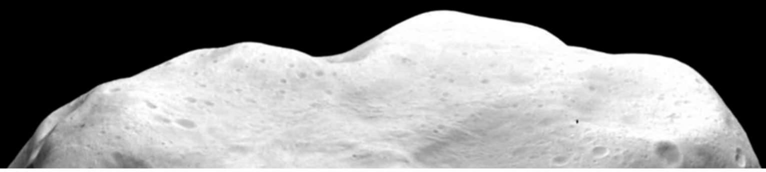


Precedents and Case Studies

Mission/Target	Target Body Summary	Staging	Descent	Ascent
NEAR-Shoemaker Landing on Eros	Large small body (33 km), weak SRP	Retrograde equatorial orbit	No passive abort with horizontal velocity biasing	N/A
Hayabusa TAG on Itokawa	Very small body (0.5 km), strong SRP	Earth-line vertical hovering	No passive abort with autonomous cross-track control	To staging
Deimos	Medium size body (15 km), dominated by Mars tides	Distant retrograde orbit	Passive abort with horizontal velocity cancellation and limited autonomy	Escape
Comet Tempel 1	Active Jupiter-family comet with known shape (6 km)	Hyperbolic flyby	Passive abort, fully autonomous descent with sensitivity to contamination	Escape
1996 FG3	Small body (1.8 km), fast rotator, small moon	Horizontal sun-line hover	Passive abort with periodic Coriolis cancellation during fully autonomous descent and sensitivity to contamination	To staging

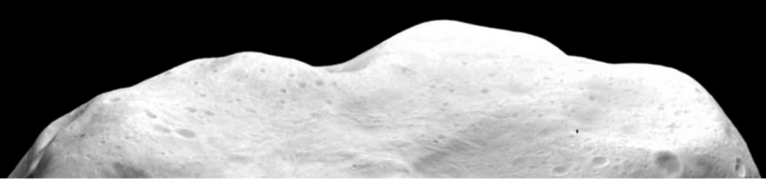
Historical Precedents: NEAR

- Not TAG
  - Objective: As much low-altitude imaging as possible.
  - Spacecraft survival not a requirement
  - No ascent planned
- Staging:
  - 35 km radius retrograde orbit
    - Eros: 34 x 11 x 11 km in extent
  - Hovering rejected due to fuel requirements
- Navigation:
  - Ground-based optical navigation
  - Autonomy considered and rejected due to need to alter flight code.
- Descent included 5 “end of mission maneuvers,” or EMMs
  - EMM-1: alter inclination and place s/c on impact trajectory
  - EMM-2 zeroed horizontal velocity at 12.2 km radius, 3.75 hrs after EMM-1
  - EMM-3 and 4: “Bouncing” braking maneuvers
  - EMM-5: Minimize landing velocity and bias horizontal velocity to keep s/c upright
- Maneuver control:
  - Timing update after EMM-1 to target EMM-2
  - Absent the update, EMM-3 and 4 would place s/c on escape trajectory



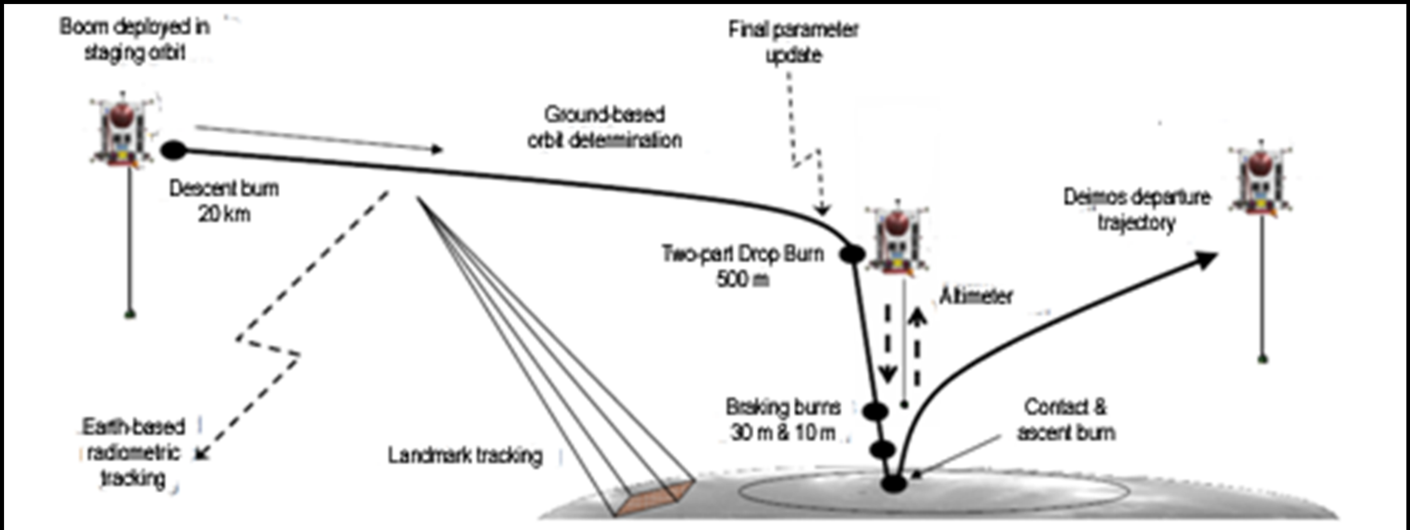
Historical Precedents: Hayabusa

- Itokawa
  - 12 hour “day”
  - 535 x 294 x 209 meters in extent
- Staging:
  - Earth-line hover
    - Motion directly observable in Doppler
    - Ground-commanded station-keeping
  - Orbits unstable due to SRP
- Descent:
  - Extension of hovering control box to include surface.
    - Manual control of real-time residuals to control velocity and timing of contact
    - Constrained sites to be through the Earth line
  - Plane-of-sky control via autonomous tracking of artificial landmark
  - Anomalous contact
- Ascent was reversal of descent.



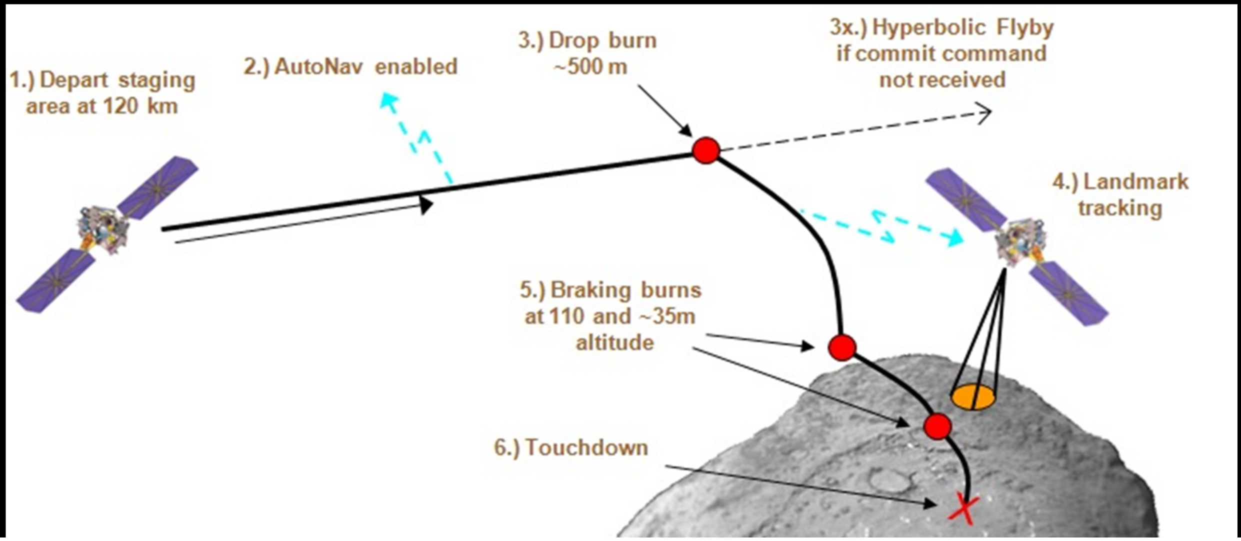
Case Study: Deimos

- Deimos:
  - Smaller and further of Martian moons
  - 15 x 12.2 x 10.4 km in extent
  - Imaged by Viking and others
- Staging:
  - 20 x 24 km equatorial DRO
  - Altitude chosen to allow sufficient time for ground-based NEAR-like navigation
  - Type was most stable option
- Descent:
  - 500 meter “flyby” at 5 m/s
  - Two-part drop burn with autonomous correction
  - Two braking burns
- Contact:
  - DRO-based design and passive abort requirement constrained sites to be sub-Mars or antipode
- Ascent:
  - Escape to Deimos-leading Mars orbit



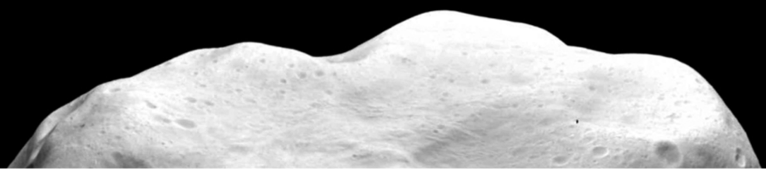
Case Study: Comet Tempel 1

- Tempel 1
  - Active Jupiter-family comet
  - Target of Deep Impact and Stardust NExT
  - 7.4 x 6.2 x 5.4 km in extent
  - Significant uncertainty in mass
- Staging
  - 3 m/s hyperbolic flyby
  - 120 km radius to 500 meter alt
  - One cleanup and AutoNav enabled
- Descent
  - “Drop burn” to send to surface
  - Two autonomous braking burns
  - Must occur while on battery power only
  - Contamination concerns
- Contact:
  - Local morning to avoid outgassing
- Ascent
  - Single burn
  - Separate cold-gas system was too expensive



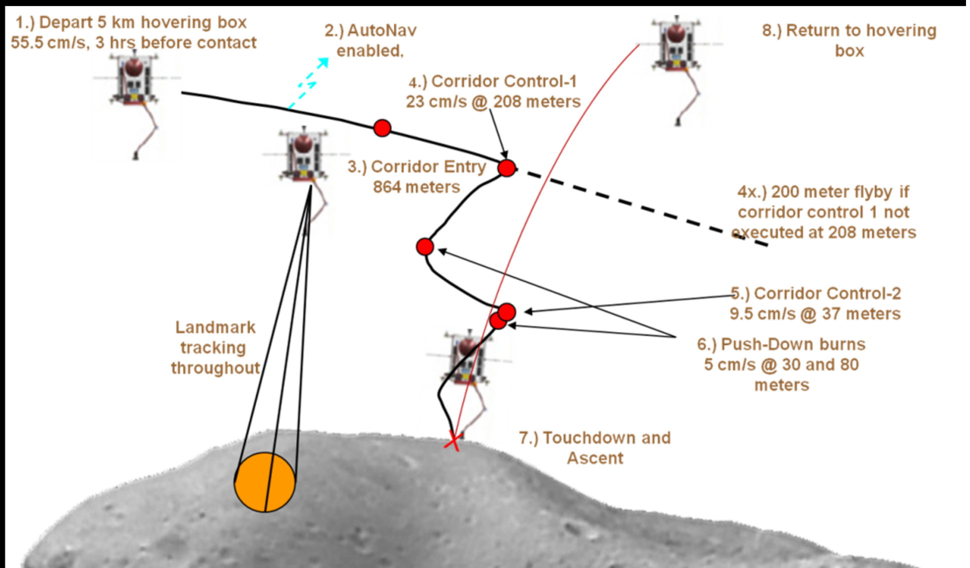
Case Study: 1996 FG3 (1)

- Unknown size/shape
  - Lightcurve data available and processed by astronomers
  - "Normalizing distance" of 720 meters
    - Primary: 756 x 684 x 504 (radii)
      - Spin: 3.6 hrs
    - Secondary: 231 x 166 x 166 (radii)
      - Orbit Radius 2.09 km
      - Period: 16.2 hrs
  - Periods well known, but $2^{1/2}$ uncertainty in distances and $2^{3/2}$ uncertainty in mass
- Unknown topography
  - Used uniform boulder distribution from Itokawa to simulate likelihood of finding landing sites
    - 19 sites with landing ellipse diamter of 6 meters
    - 0 sites with landing ellipse diameter of 10 meters
    - Admittedly conservative because it neglects sorting mechanisms
  - Concluded that the landing location dispersions needed to be as small as possible.



Case Study: 1996 FG3 (2)

- Staging
  - "Horizontal hover" at 5 km radius, ±45 deg off sun-line
  - Simplified phasing to keep Secondary on far side of Primary during TAG and meet lighting requirements at contact
- Descent
  - Two "corridor correction" maneuvers to counter strong Coriolis effect
  - Two "push down" maneuvers to bias trajectory for contamination
- Contact
  - Context imaging required mid afternoon or morning contact
  - Mid morning selected to keep entire trajectory over sun-lit surface
- Ascent
  - Single burn to return to 5 km altitude within 5 hours including contact disturbances
  - On escape trajectory



Any Questions?